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辽宁西部早白垩世义县组一新驰龙类[1)]

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摘要: 我国辽西早白垩世义县组底部陆家屯层近年来产出大量恐龙和其他脊椎动物化石,其中包括兽脚类恐龙当中的伤齿龙类和窃蛋龙类(Xu, 2002)。本文报道该层位产出的一件驰龙类化石标本。通过对比研究,我们确认这一标本不同于热河群已知的其他 3 种驰龙类,并建立了驰龙类的一个新属种:陆家屯纤细盗龙(*Graciliraptor lujiatunensis* gen. et sp. nov.)。

驰龙类最初发现于北美晚白垩世地层中(Matthew and Brown, 1922),随后在蒙古晚白垩世地层中也有发现(Osborn, 1924);现在已知驰龙类的化石记录主要集中在北美和中亚地区的白垩纪地层中(Xu, 2002)。千禧中国鸟龙(*Sinornithosaurus millenii*)曾代表最早的确定无疑的驰龙属种(Xu et al., 1999),其生存时代大约为 125 Ma (Swisher et al., 1999)。陆家屯纤细盗龙正型标本产于义县组底部陆家屯层,其上覆和下伏岩层的同位素年代分别为 128 Ma 和 139 Ma (Swisher et al., 2001)。因此,陆家屯纤细盗龙代表已知最早的驰龙属种。

陆家屯纤细盗龙和其他驰龙类共享以下近裔特征:尾椎前关节突和脉弧极度加长、上颌齿后缘锯齿明显大于前缘锯齿和指节 III - 2 明显缩短。陆家屯纤细盗龙的以下近裔特征区别于其他驰龙类:中部尾椎有一板状结构连接左右后关节突、中部尾椎椎体极细长(椎体长度和宽度比率约 8.6)、第 1 指爪明显小于第 2 指爪、第 3 掌骨近端明显膨大、胫骨细长(估计的长度和中部骨干直径比率约为 28)、胫骨近端骨干横截面方形、距骨内髁明显向后膨大和第 2 跖骨远端明显宽于其他跖骨。

系统发育分析表明辽西的驰龙类构成一个单系类群。这一类群代表驰龙类的一个早期分支,对于了解驰龙类的早期演化具有重要意义。一方面,辽西驰龙类的发现为鸟类和驰龙类具有很近的亲缘关系提供了更多证据。辽西驰龙类桡骨明显比尺骨纤细,半月形腕骨主要与第 2 掌骨关联,第 1 手指明显缩短以及趾爪弯曲度大,这些特征与早期鸟类非常相近(Chiappe et al., 1996)。另一方面,辽西的驰龙类也显示出与伤齿龙类的更多相似性,比如它们后足和尾椎的一些特征相对其他驰龙类而言更接近伤齿龙类(Norell and Makovicky, 1997)。辽西驰龙类的发现虽然大大缩短了驰龙类、鸟类和伤齿龙类的形态差距,但也为这些类群的演化带来了更多的不相容性,表明向鸟类演化的过程是不均一的。

陆家屯纤细盗龙代表发现于热河群的第 4 种驰龙类,显示了驰龙类在早白垩世时期具有很高分异度。但已知的早期驰龙类在形态上非常相似,结合其他方面的证据,推测驰龙类的早期演化以快速分异为特征,这似乎不同于其姐妹群——伤齿龙类,相对而言,伤齿龙类的早期演化以快速的形态变化为特征。

关键词: 辽宁西部,早白垩世,义县组,驰龙类

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A NEW DROMAEOSAUR (DINOSAURIA: THEROPODA) FROM THE EARLY CRETACEOUS YIXIAN FORMATION OF WESTERN LIAONING

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Abstract A specimen collected from the Early Cretaceous lowest part of Yixian Formation of Liaoning, northeastern China, represents a new genus and species of dromaeosaurid theropod. It comprises a fragmentary maxilla with some teeth, a few caudals, almost complete fore limbs, and partial hind limbs and is here named *Graciliraptor lujiatunensis* gen. et sp. nov. Distinctive characteristics of the new species include a laminal structure connecting the postzygapophyses of middle caudals, middle caudals extremely long and slender, small manual ungual I, proximal end of metacarpal III strongly expanded, proximal tibiotarsus shaft rectangular in cross section, astragalar medial condyle significantly expanded posteriorly, metatarsal II distally much wider than the other metatarsals and long and slender pedal phalanx III-1. Being the earliest definitive dromaeosaurid species known to date, *G. lujiatunensis* provides new information important for understanding the early evolution of the group. On one hand, *G. lujiatunensis* displays a few features similar to those of basal birds, such as caudals significantly elongated, semilunate carpal small and primarily contacting metacarpal II, and manual digit I short, providing further evidence for a close relationship between the Dromaeosauridae and the Aves; on the other hand, it is similar to troodontids in some features on the caudals. The discovery of *G. lujiatunensis* also indicates a high diversity of the Dromaeosauridae in the Early Cretaceous Jehol Biota. Combined with other lines of evidence, it is inferred that the Dromaeosauridae rapidly diversified taxonomically but remained relatively stable morphologically in the early evolution of the group.
Key words Western Liaoning, Early Cretaceous, Yixian Formation, Dromaeosauridae

1 Introduction

Originally discovered from the Late Cretaceous North America (Matthew and Brown, 1922), dromaeosaurids are now known to have a much wider distribution both geographically and stratigraphically (Osborn, 1924; Sues, 1978; Barsbold, 1983; Kirkland et al., 1993; Perle et al., 1999; Xu et al., 1999, 2000). The earliest fossils definitively referable to the Dromaeosauridae are from the shales of the lower Yixian Formation (Xu et al., 1999; Ji et al., 2001), which is dated as about 125 Ma (Swisher et al., 1999). Here we describe a new dromaeosaurid specimen that was collected from the lowest part of the Yixian Formation that is at least 3 million-year older than *Sinornithosaurus*-fossil-bearing beds (Swisher et al., 2001). It is therefore the oldest definitive dromaeosaurid, and allows us to review the distribution of some characters that are important for understanding the early evolution of the Dromaeosauridae.

2 Systematic paleontology

Theropoda Marsh, 1881
Maniraptora Gauthier, 1986
Dromaeosauridae Matthew et Brown, 1922
Graciliraptor lujiatunensis **gen. et sp. nov.**
(Figs. 1～3)

Holotype IVPP V 13474 (Institute of Vertebrate Paleontology & Paleoanthropology, Bei-

jing) , a fragmentary maxilla with some teeth , a few caudals , almost complete forelimbs , and partial hindlimbs.

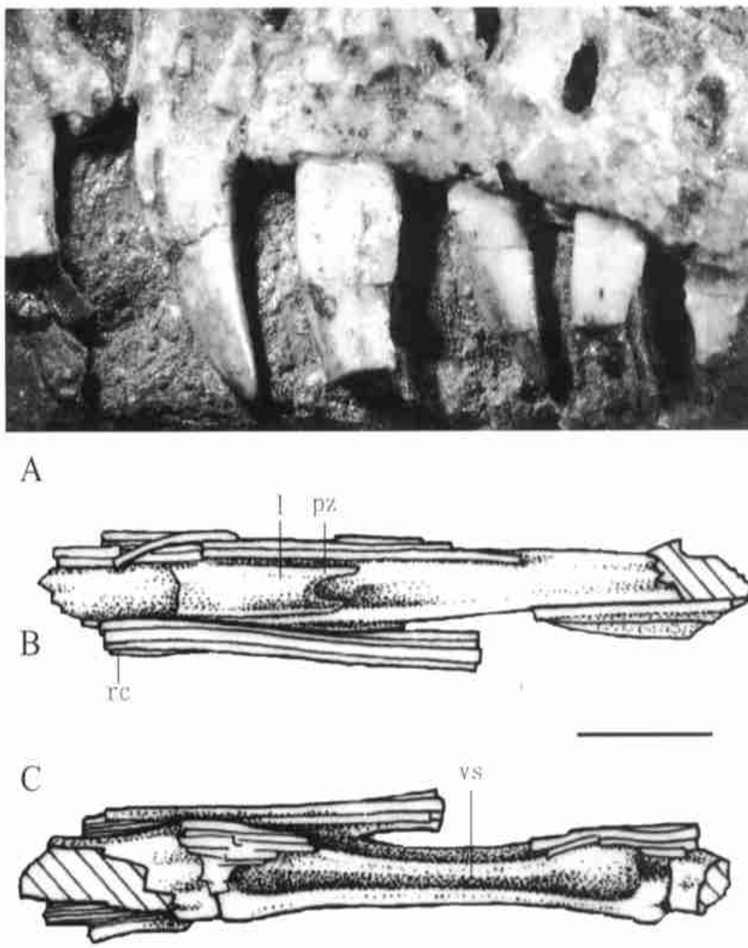


图 1 陆家屯纤细盗龙(新属新种)正型标本(IVPP V 13474) ,比例尺 = 1 cm

Fig. 1 Holotype of *Graciliraptor lujiatunensis* gen. et sp. nov. (IVPP V 13474) , scale bar = 1 cm

A. 上颌齿外侧视 some maxillary teeth in lateral view; B. 中部尾椎背视 dorsal view of middle caudals; C. 中部尾椎腹视 ventral view of middle caudals

简字说明 Abbreviations:l. lamina 板状结构;pz. postzygapophysis 后关节突;rc. rod-like extensions of caudals 尾椎的棒状结构;vs. ventral sulcus 腹沟

Etymology The generic name is derived from the slender limbs and tail of the animal (gracilis , L. slender) , and the suffix "*raptor*", commonly used for dromaeosaurid dinosaur names. The specific name "*Lujiatun*" refers to the village near which the holotype was found.

Locality and horizon Lujiatun , Beipiao City , western Liaoning , China ; the lowest member of the Yixian Formation (Hauterivian ; Swisher et al. , 1999 , 2001) .

Diagnosis *Graciliraptor lujiatunensis* can be differentiated from all other known dromaeosaurid species based on the following derived features : a laminal structure connecting the postzygapophyses of middle caudals ; extremely long and slender middle caudals ; ungual of manual digit I much smaller than that of manual digit II ; proximal end of metacarpal III strongly expanded ; extremely slender tibiotarsus ; proximal tibiotarsus shaft rectangular in cross section ; astragalar medial condyle signifi-

cantly expanded posteriorly; metatarsal II distally much wider than the other metatarsals; and long and slender pedal phalanx III-1.

3 Description

The holotype of *G. lujiatunensis* might represent an adult animal as indicated by the partial fusion of the astragalus and calcaneum to the tibia.

The skull is represented only by a partial left maxilla with a few teeth (Fig. 1A). The anterior teeth appear to have no serrations on both anterior and posterior carinae, but the tips are all broken and these might have been serrated. The middle and posterior teeth are similar to those of the velociraptorines in that the posterior serrations are significantly larger than the anterior ones (Currie, 1995).

Ten caudals are preserved on the holotype. The centra of the middle caudals are significantly elongated (Figs. 1B, C). As in other dromaeosaurids, the prezygapophyses are extremely long, forming bundle-like structures. Unusually a laminal structure is developed connecting the two postzygapophyses, covering the anterior one-eighth of the succeeding caudal. The chevrons attached to the middle caudals are similar to those of other dromaeosaurids in forming a rod-like structure except for some minor differences such as that both anterior and posterior processes of the chevrons are bifurcated in ventral view and the posterior process appears also to be elongated, though not as elon-

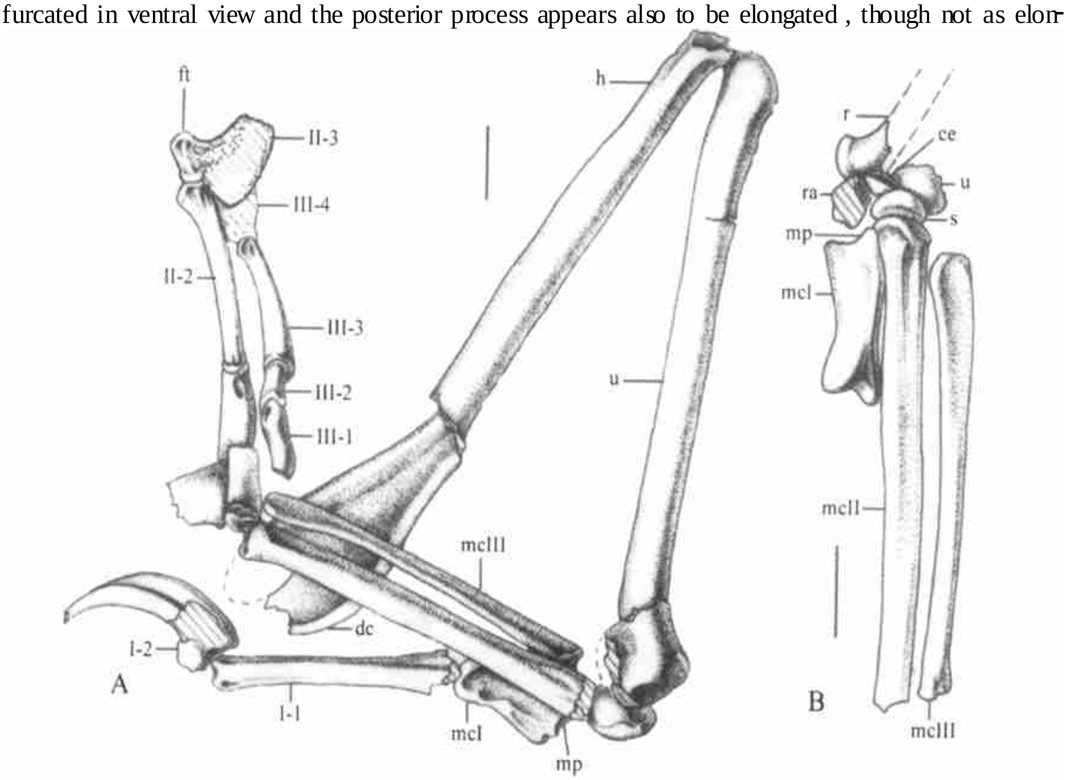


图 2 陆家屯纤细盗龙(新属新种)正型标本(IVPP V 13474),比例尺 = 1 cm

Fig. 2 Holotype of *Graciliraptor lujiatunensis* gen. et sp. nov. (IVPP V 13474), scale bar = 1 cm

A. 右前肢 right forelimb; B. 左前肢 left forelimb

简字说明 Abbreviations: ce. centrale 中央骨; dc. deltopectoral crest 三角胸嵴; ft. flexor tubercle 屈肌结节; h. humerus 肱骨; I-1 to III-4. manual phalanx I-1 to III-4 指节 I-1～III-4; mc I-III. metacarpal I-III 第1～第3掌骨; mp. medial projection 内侧突; r. radius 桡骨; ra. radiale 桡侧掌骨 s. semilunate carpal 半月形腕骨; u. ulna 尺骨

gated as the anterior process.

An almost complete right forelimb and a partial left forelimb were preserved on the holotype, including some carpal elements (Fig. 2). The humerus is long and slender, with a relatively short deltopectoral crest. The ulna is comparatively long, about 86 % the humeral length, which is proportionately longer than that in other dromaeosaurids. The radius is much thinner than the ulna, about 53 % the thickness of the latter at the mid-length. The manus is long, about 130 % the length of the humerus, a ratio larger than that in other dromaeosaurids (Xu, 2002). The semilunate is small in size compared with most other non-avian maniraptorans, covering only the proximal end of metacarpal II. Metacarpal I is stout and short, less than one third the length of metacarpal II. Metacarpal II is long and comparatively robust. Metacarpal III is slightly shorter and much thinner than metacarpal II, and is bowed laterally. Unlike in other dromaeosaurids, the proximal end of metacarpal III is quite deep dorsoventrally, even deeper than that of metacarpal II. The manual phalangeal formula is 2-3-4 as in most coelurosaurians. Manual phalanx I-1 is relatively short. Phalanx I-2, the ungual of digit I, is strongly curved, and has a moderately developed flexor tubercle proximoventally and a lip proximodorsally. Phalanx II-1 is the most robust of the phalanges. Phalanx II-2 is longer than phalanx II-1. Phalanges of digit III are much thinner than those of digit II. Phalanx III-1 is significantly longer than phalanx III-2. As in some dromaeosaurids, a prominent ventral heel is present on the proximal end of phalanx III-2.

Most of the left tibiotarsus and part of the right tibiotarsus and femur are preserved (Figs. 3A～D). The most conspicuous feature of the tibiotarsus is its slenderness. The estimated length/midshaft-diameter ratio is about 28, larger than that in all known non-avian theropods. The proximal end of the tibiotarsus is not preserved and the preserved proximal shaft is sub-quadrangular and the distal shaft oval in cross section. In anterior view the fibular crest is straight for most of its length

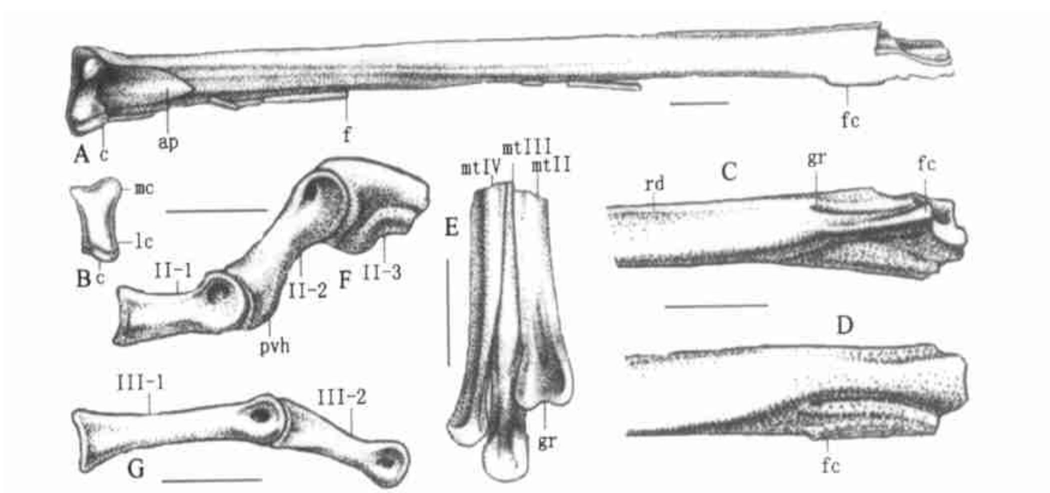


图 3 陆家屯纤细盗龙(新属新种)正型标本(IVPP V 13474) ,**比例尺** = 1 cm

Fig. 3 Holotype of *Graciliraptor lujiatunensis* gen. et sp. nov. (IVPP V 13474), scale bar = 1 cm

A. **左侧胫跗骨和腓骨前视** left tibiotarsus and fibula in anterior view; B. **左侧距骨和跟骨远端视** left astragalus and calcaneum in distal view; C. **右侧胫跗骨外侧视** right tibiotarsus in lateral view; D. **右侧胫跗骨后视** right tibiotarsus in posterior view; E. **左侧跖骨腹视** left metatarsus in ventral view; F. **左侧第 2 趾内侧视** left pedal digit II in medial view; G. **右侧** III-1 **和** III-2 **趾内侧视** right pedal phalanges III-1 and III-2 in medial view

简字说明 Abbreviations: ap. ascending process **上升支**; c. calcaneum **跟骨**; f. fibula **腓骨**; fc. fibular crest **腓骨嵴**; gr. groove **槽**; II-1 to III-2. pedal phalanx II-1 to pedal phalanx III-2 **趾节** II-1～III-2; lc. lateral condyle **外髁**; mc. medial condyle **内髁**; mt II-IV. metatarsals II-IV **第 2～第 4 跖骨**; pvh. proximoventral heel **近端腹跟突**; rd. ridge **脊**

rather than convex laterally as in most other theropods. The astragalus has a much larger medial condyle relative to the lateral one, which is significantly expanded posteriorly.

Both the left and right pes are partially preserved (Figs. 3E～G). In general, the pes is similar to that of other basal dromaeosaurids and troodontids in having a partial arctometatarsus (Holtz, 1994; Xu, 2002). Unlike other dromaeosaurids (Xu, 2002), metatarsal II is distally much wider than metatarsals III and IV. The distal end of metatarsal II is strongly ginglymoid. The shaft of metatarsal III is subtriangular in cross section due to the extremely narrow ventral margin and it is inferred to be similar to some basal dromaeosaurids and troodontids in having a pinched proximal end, though its proximal portion is missing. Unlike most other dromaeosaurids, the distal end of metatarsal III is not ginglymoid. Metatarsal IV is the most slender element among the metatarsals. The pedal phalanx II-1 and II-2 are much more robust than the other pedal phalanges and the latter is longer than the former. The ungual of pedal digit II is enlarged as in other dromaeosaurids and troodontids. Pedal phalanx III-1 is long and slender, about twice as long as the pedal phalanx II-1. A noteworthy feature is the medial condyle of the distal end is much larger than the lateral condyle.

4 Discussion

Although the holotype, the only specimen of the species, preserves a small part of the skeleton, it does provide many phylogenetic signals.

The dromaeosaurid status of *G. lujiatunensis* is indisputably indicated by the presence of extremely elongated prezygaphophyses and chevrons that is unique to dromaeosaurid dinosaurs among theropods (Ostrom, 1990; Xu, 2002). Other features suggesting the dromaeosaurid affinities of *G. lujiatunensis* include: significant size difference between the anterior and posterior denticles on the maxillary teeth and manual phalanx III-2 significantly shortened. Significantly shortened manual phalanx III-2 is a feature previously unnoticed for diagnosing the Dromaeosauridae. Primitively in theropods, the length difference between manual phalanx III-1 and III-2 is minor, usually with the former slightly longer than the latter. Dromaeosaurids have much shorter manual phalanx III-2 relative to phalanx III-1 (Ostrom, 1969; Norell and Makovicky, 1997, 1999; Xu et al., 1999). Liaoning dromaeosaurids such as *Sinornithosaurus* and *G. lujiatunensis* have an even shorter phalanx III-2.

G. lujiatunensis shows many distinctive features distinguishing it from other dromaeosaurids. The most conspicuous feature is that it might represent the most slender skeleton among non-avian theropods found to date. In general, coelurosaurians are more slender than other non-avian theropods. *G. lujiatunensis* is among the most gracile coelurosaurs. The middle caudals have a centrum length/width ratio of about 8.6, which is the largest among known non-avian theropods; the tibiotarsus has an estimated length/midshaft-diameter ratio of about 28, suggesting an extremely slender tibiotarsus; most pedal phalanges are elongate relative to the maximum depth or width, without significantly expanded articular ends. These data, together with the data that it is a small sized animal, suggest that *G. lujiatunensis* is extremely light in build, which represents an important evolutionary trend towards birds (Sereno, 1999; Xu et al., 2000).

The other diagnostic feature of *G. lujiatunensis* include a laminal structure connecting the two postzygapophyses of middle caudals, small manual ungual I, proximal end of metacarpal III strongly expanded, the proximal tibiotarsus shaft rectangular in cross section, astragalar medial condyle significantly expanded posteriorly, and metatarsal II distally much wider than the other metatarsals. Usually in dinosaurs the tibiotarsus shaft is sub-oval in cross section. The proximal section of the tibiotarsus shaft bears distinctive ridges between which the shaft is flat, thus forming a rectangular cross section. This feature represents an apomorphy for the taxon. The medial condyle of the astragalus of *G. lujiatunensis* is significantly enlarged not only anteriorly as in other coelurosaurs but posteriorly, and it is about 1.7 times as thick as the lateral condyle. The other interesting diagnostic

feature is metatarsal II distally much wider than the other metatarsals. The transverse width of the distal articulation of metatarsal II is about 1.5 times and 2 times that of metatarsal III and IV, respectively. Metatarsal II is either subequal to or more slender in robustness than the other metatarsals in most other theropods including other dromaeosaurs.

Among the known dromaeosaurid taxa, *G. lujiatunensis* is most closely related to two other dromaeosaurids from Liaoning (*Sinornithosaurus* and *Microraptor*) because they share a number of derived similarities that are absent in other dromaeosaurs. For example, radius significantly thinner than ulna, ungual of manual digit III much smaller than that of manual digit II, manual digit I significantly shortened, manual phalanx III-2 extremely short, and presence of proximoventral heel on manual phalanx III-2. Primitively in theropods manual digit I is long and robust. *G. lujiatunensis* is similar to *Sinornithosaurus* and *Microraptor* in having a short manual digit I with the ratio of the combined length of metacarpal I and phalanx I-1 to metacarpal II length less than 1; in birds other than *Archaeopteryx* and *Confuciusornis* this ratio is also less than 1 (Chiappe et al., 1999; Wellnhofer, 1992, 1993). There are also some pleisomorphic similarities between *G. lujiatunensis* and the other Liaoning dromaeosaurs. For example, the pedal phalanx II-2 is not highly abbreviated and the second pedal ungual is proportionately smaller relative to that of most other dromaeosaurs. A phylogenetic analysis suggests that all known Liaoning dromaeosaurs including *G. lujiatunensis*, *Sinornithosaurus*, and *Microraptor* form a monophyletic group which is the sister group to all other dromaeosaurid taxa (Fig. 4; for details see Xu, 2002).

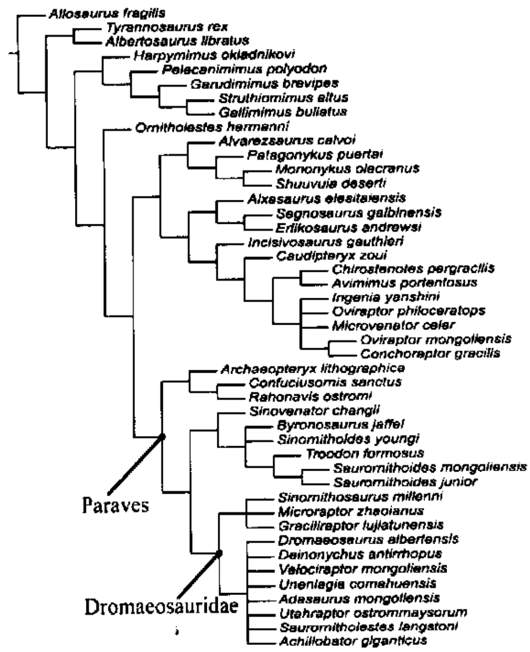


图 4　陆家屯纤细盗龙(新属新种)的系统位置

Fig. 4　A strict consensus tree of 132 most parsimonious trees (tree length = 737; CI = 0.43; RI = 0.68) showing the phylogenetic position of *Graciliraptor lujiatunensis* gen. et sp. nov.

The analysis is based on a dataset of 45 taxa and 260 characters; see Xu, 2002 for more detailed information

A few characters of *G. lujiatunensis* deserve comments here. Although the caudals of some troodontids, some dromaeosaurs, and *Archaeopteryx* (Wellnhofer, 1993) are not as elongated as those of *G. lujiatunensis*, they are comparatively much longer than in most other theropods. Elongation of the middle caudals may represent an apomorphy for the Paraves. In some features, the caudals of *Graciliraptor* are more troodontid-like than dromaeosaurid-like. The middle caudals have no neural spine, instead they bear a shallow groove on the dorsal surface; ventrally the middle caudal bears a deep sulcus. These features are all seen in middle caudals of troodontids and provide further evidence for a close relationship between dromaeosaurids and troodontids. On the other hand, *G. lujiatunensis* displays a few avian features. Primitively in theropods the thickness difference between the ulna and radius is minor. The ratio of diameter of radius shaft to ulna shaft is approximately 0.8 in *Allosaurus*, 0.9 in *Gallimimus*, 0.8 in oviraptorosaurs, 0.9 in therizinosauroids, and more than 0.8 in most dromaeosaurs and troodontids. In more basal theropods the radius is subequal to the ulna in thickness. In birds, the radius becomes significantly thinner than the ulna, with a ratio of less than 0.7 (Chiappe et al., 1996). *Archaeopteryx* retains the primitive condition, with a ratio of

about 0.8. The radius is very thin in *G. lujiatunensis*, like other dromaeosaurs from Liaoning, less than 60 % as thick as the ulna, which is a feature seen in advanced birds (Chiappe et al., 1996). The size and position of the semilunate carpal are variable among maniraptorans. The semilunate is large and covers proximal ends of both metacarpal I and II in most non-avian maniraptorans and *Archaeopteryx*, though in the latter taxon it is more centered on metacarpal II (Martin, 1991). In most birds such as *Confuciusornis* (Chiappe et al., 1999), it is small and fused with proximal end of metacarpal II. The semilunate carpal of *G. lujiatunensis* displays a derived condition among maniraptorans in having a small-sized semilunate which articulates to the proximal end of metacarpal II. A pronounced projection is present on the proximal end of metacarpal I. This projection is medially positioned and forms a smooth convex articular surface of the metacarpus together with the proximal end of metacarpal II. This feature is also seen in some basal birds and may represent a further modification toward a fully flexed arm. The discovery of *G. lujiatunensis* as well as other dromaeosaurs from Liaoning provides further evidence for a close relationship of the Dromaeosauridae, Troodontidae and Aves. On one hand, new discoveries further shorten the morphological distance between the groups; on the other hand, they bring more incongruence among these groups, suggesting an uneven evolution toward the transition to birds.

G. lujiatunensis represents the fourth named dromaeosaurid taxon from the Jehol Biota, suggesting that the dromaeosaurids highly diversified in Early Cretaceous. The temporal distributions of the three paravian groups combined with character distributions among the basal dromaeosaurids and troodontids indicate that the basal deinonychosaur split might not be significantly earlier than Hauterivian, possibly in the earliest Cretaceous (Xu and Wang, in submission). If this is the case, the Dromaeosauridae possibly had a relatively rapid taxonomical diversification within the Early Cretaceous. However, the known early dromaeosaurids are similar in morphology, suggesting a relatively slow morphological change. Interestingly, the Troodontidae, which was suggested by many studies to be the sister-group of the Dromaeosauridae (Gauthier, 1986; Sereno, 1999; Xu, 2002), seems to have a rapid rate of character evolution at the base of the group (Xu and Wang, in submission). These data suggest that the two deinonychosaurian groups might have different evolutionary patterns in their early history.

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